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SUMMARY REPORT OF A STUDY OF MISSION DURATION EXTENSION PROBLEMS

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NORTH AMERICAN ROCKWELL CORPORATION

Volume IV

SD 67-478-4

FOREWORD

This volume, Volume IV of a four-volume report, summarizes the results of a twelve-month study of manned space mission duration extension problems conducted between 1 October 1966 and 1 October 1967.

This material was developed under a company-funded effort with the intent of determining the requirements and constraints imposed on man, the mission, and the mission subsystems, by extending manned space missions to 700 days duration, using contemporary hardware. The study was conducted in conjunction with that of the Manned Planetary Flyby Missions based on Saturn/Apollo Systems (NAS8-18025 was conducted for NASA/MSFC by NAR/SD) during the same time period.

The Systems Engineering Management department of the Space Division of the North American Rockwell Corporation, performed the study under Research Authorization RA 2195-15400. Documentation was contracted for by the Mission Analysis Division of NASA/OART, Ames Research Center, Moffett Field, California under contract NAS2-4214.

Roy B. Carpenter, Jr., who was both program manager and project engineer, Systems Engineering Management, Research, Engineering and Test Division of NR/SD, directed the work. Contributions were provided by many SD and subcontractor personnel as indicated in the appropriate volumes.

The value of this study cannot be measured by the investment made by either NR/SD or the NASA because of the subcontractor participation. It has been estimated that the total involved effort exceeds that of a 12-man-year contracted study.

CONTENTS

ILLUSTRATIONS

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TABLES

1.0 INTRODUCTION

1.1 BACKGROUND

The Space Division of the North American Rockwell Corporation has been studying the problems associated with extending space mission durations for the past five years. These studies have been addressed to the planetary exploration problem and have attempted to identify the problem areas as well as the best mission/system concept and the associated experiment programs. Closely associated with these studies, and at times a part of these studies, are the investigation into system failure mechanics and the reliability/crew safety improvement effort.

As the result of one such effort conducted under a NASA/MSC contract (NAS 9-3499) a concept was developed which seems to facilitate a mission system design that would assure safe missions and be nearly independent of the duration. As a result, an addendum to that contract was awarded to SD to make application of the concept to one system and demonstrate feasibility. This was successfully accomplished in June 1965.

The subsequent Mars-Venus study, NAS 8-18025, was awarded to SD in Aug. 1966. However, it did not include provisions to continue the duration extension effort. SD elected to conduct that aspect of the study on company funds. The MAD of NASA/OART elected to fund the documentation of the SD company-funded effort and to sponsor several briefings. The results of these efforts are summarized in this volume.

1.2 THE OBJECTIVES

This study was conducted with three main objectives in mind:

1. To demonstrate the feasibility of extended duration space missions through the application of the Availability Concept to a mission/system design.

2. To determine the extended mission capability using contemporary hardware.

3. To develop a more quantitative assessment of the following factors as they affect achievement of a probability of safe return of 0.99.

   a. Space mission extension capability as a function of the maintenance and repair concept.

b. The quantity of maintenance and repair actions to be expected and prepared for and the resultant crew work load.

c. The type of maintenance and repair actions required of the crew, specifically as it affects extravehicular activities.

d. The weight penalty imposed on the mission system as the result of having to perform maintenance actions.

e. The potential advantages of selecting the optimum operational concept as it affects crew safe return.

f. The effects of potential design improvements.

4. As a secondary objective, it was deemed desirable, in general, to make applications of the results to Earth Orbital missions.

1.3 THE DATA BASELINE

One of the most difficult problems encountered in the assessment of mission safety and reliability is in selecting the data base. Historically, the data is taken from the available failure rate tables. As a result, the assessment may or may not bear any resemblance to the design situation. Because of the circumstances involved, there is usually no other alternative, but the results are always suspect.

The Apollo program is now in its fifth year and data is now available to facilitate a valid analysis of space mission capability which is representative of the actual situation for the 1970 time period. These systems have from 5,000 to 25,000 hours of test data at the system level and from 20,000 to over one million hours at the lower levels of assembly. As a result, statistical confidence can be established in the veracity of the predicted mean time before failure, their qualification status and space rating.

Apollo systems and components were used to synthesize systems designs and the relevant data provided the basis for estimating contemporary hardware capability and the support requirements.

The attractiveness of this approach can be readily understood when it is realized that the commonality in critical system functional requirements make projections from one mission to any number of diverse missions possible, with little compromise in the results — given that the data base was valid. Further, because the specific potential problem areas are identified, specific application can even be made to unmanned missions.

> NOTE: A word of caution must be interjected here in terms of application of these data. Although the numerics applied are the best available, they are only estimates and, in particular, the effects of long duration spaceflight are yet to be determined—for the majority of components.

1.4 THE EXTENDED MISSION PROBLEM

SD studies over the past few years have shown conclusively that it is impractical to attempt to design a failure-free spacecraft for missions approaching or exceeding one year in duration. The results of these studies are expressed by the curves and data of Figure 1.1. Further, the data in indicates that, during the next decade, it may be impractical to attempt design of a spacecraft for maintenance-free operations for missions in excess of even 45 days. The practical mission limits for a non-maintainable design for a manned spacecraft depend on the selected mission profile and objectives.

As missions are extended in time and the abort profiles become more complex and time consuming, equipment failure becomes virtually certain. Further, a point is reached where adding redundancy no longer compensates for potential failures. Rather, this adds to the failure hazard. This technology limit is created by the need to include switching devices, performance monitors and voting circuits, as well as the wiring or plumbing, into the function reliability assessment. The practical limit seems to be between two and three components in simple redundancy. Beyond this point, maintenance must be considered as a more reasonable alternative, if for no other reason than the reduced operational complexity.

This study is concerned with mission durations measured in years. The approximate mission reliability requirements, in terms of mean time before failure (MTBF), disregarding maintenance, are shown below.

		MTBF'S TIMES 10^4 HOURS
CAPABILITY	STATE-OF-ART	= 0.1 TO 1.0
	OPT REDUNDANCY	= 1 TO 5.0
REQUIREMENTS	VENUS REQ	= 20 TO 100
	MARS REQ	= 20 TO 1000

As indicated, if no failures are to be tolerated, these estimates fall far short of the expressed requirements — literally by orders of magnitude. Further, this same study indicated that, on the average, system MTBF can be improved over any decade by factors of between 5 and 10. The effect of applying those systems to the longer space missions are as indicated on Figure 1. 1.

Obviously, reliability improvements do not hold the complete answer and the longer missions must be prepared for failures. Some study results have suggested that a possible alternative would include abort, spacecraft replacement, escape capsules, or rescue. But, for the planetary and many lunar area missions, none of these will assure crew survival because of the long recovery times required.

Since failures are to be expected, it would be well to understand the mechanics of failure. Reliability estimates are misleading because if a failure seems probable, the impression created leaves one with a feeling of impending catastrophe; but, this is usually far from the truth. Refer to Figure 1. 2 where a plot of system function status is presented as a function of mission elapsed time. Note that when a failure occurs, usually only one function within that system is affected. At times several functions are affected, but it is most unlikely that a whole system or any subsystem will

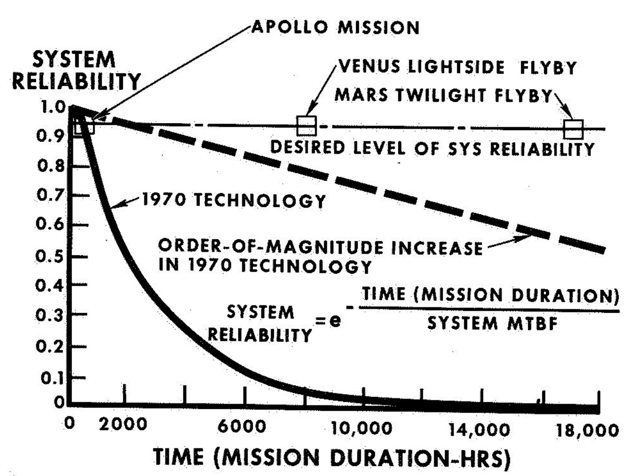


Figure 1. 1 The Mission Extension Problem

Figure 1. 1. The Mission Extension Problem

fail completely. Note too that the term "availability" expresses the average value or the potential availability of the system(s). This term is a goal measure of the effectiveness of maintainable designs.

In considering the merits of a maintenance concept it is also essential to know how many failures are likely to occur. Figure 1.3 presents these data as a function of mission duration and the required level for the probability of safe return (P_s). Note that for $P_s \geq 0.99$ about 270 failures must be planned for the two-year mission even though less is expected.

It is evident that failures must be anticipated and repair expected. Also, that the effects of failure will normally be limited to one function, and that the number of failures or subsequent repair actions will be modest — perhaps less than one in three days.

1.5 THE AVAILABILITY CONCEPT

The availability concept is a design or mission analysis technique that facilitates the determination of an optimum man-machine relationship. Mission effectiveness is maximized through establishment of a safe and reasonable balance between system and mission performance, operation control, reliability, and maintainability. Application of this concept can result in a mission/system design that provides maximum operational availability of the system functions within the constraints imposed by crew capabilities, mission requirements, and existing technology, thus maximizing the potential mission success and crew safety.

The availability concept as an analytical/design tool is presented in logic form in Figure 1.4. Before application, the system reliability/safety logic has been prepared in simplified form, with the weak links* identified in order of weakness. Then, starting with the weakest, the analytical logic is applied to each block ($x.x.x._i$) in sequence, until the safety/success goal is achieved, or surpassed. A detailed explanation is given in Volume I of this report and applied to individual systems in Volume III.

The key to the analysis is to determine what level of assembly to work on, and the most effective/safe corrective action required to reduce a failure hazard. Each weak link must be treated as an individual case; the most probable failure modes are isolated, and then appropriate action determined. Computers can only be used in a bookkeeping role because each decision must be made, based on the specific situation. A spare will not always be appropriate.

*Weak Links are the more failure prone components of a system.

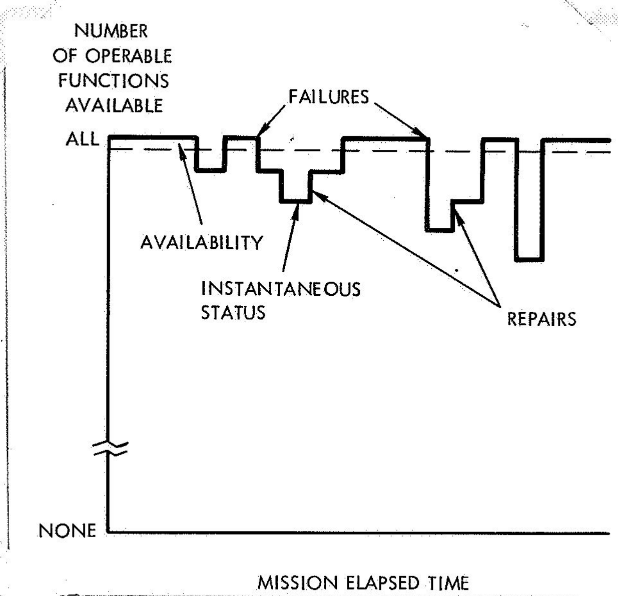


Figure 1.2 System Failure Physics Where Repair is Permitted

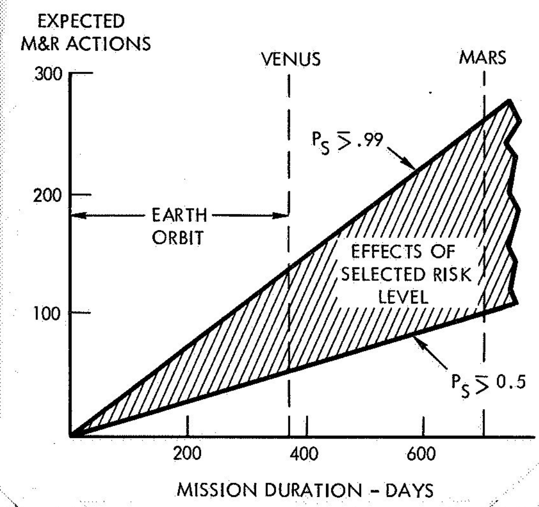


Figure 1.3 Estimating the Unscheduled Maintenance Work Load

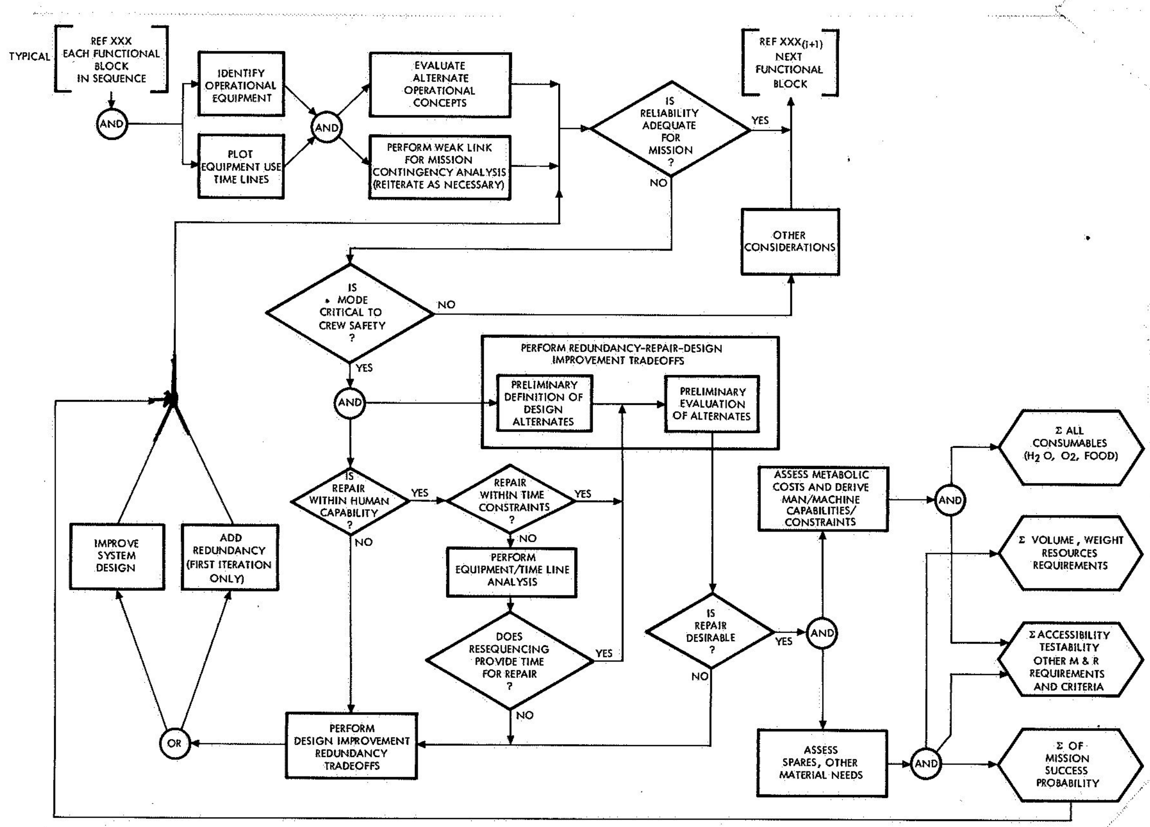


Figure 1.4 System Reliability/Safety Logic

The selection criteria must include accessibility, least number of spares per weak link, least number and complexity of repairs per weak link, ease of maintenance, least redundancy, and simple monitoring and diagnosis. Redundancy is a less desirable alternative because interchangeability of spares is reduced. The process of selecting the level of assembly for maintenance can have a profound influence on the resulting mission requirements. To assure maximum mission efficiency, it is necessary to determine how failure risk is distributed within the specific system, functions, assemblies, or parts. From the example of Figure 1.5, note that only one function displays a low reliability at the system level. Further, only one assembly still contributed most of the failure hazard. However, at the part level, three assemblies exhibit equal risk of failure. The one assembly which contains all those parts could be spared, or the three parts could be spared. Thus, the choice was an obvious one since the spare assembly is small and lightweight, easy to diagnose, and easy to replace.

Obviously, the concept depends on the ability to perform maintenance and repair. Therefore, in order to facilitate an understanding of this aspect of the problem, it is desirable to review the logical process associated with system failure and correction. These activities are presented in Figure 1.6. Note that the darker blocks indicate those data derived during this study. From this, it is evident that the following requirements and constraints must be defined and satisfied.

1. A spare parts complement is provided to meet the repair and replacement needs to a risk level compatible with the mission goals.

2. A performance monitor is designed to facilitate identification of system malfunctions when and where they are most likely to occur.

3. Diagnostic equipment is designed to isolate malfunctions in the potentially weak system functions.

4. Tools are selected to aid the crewman in making the M&R action within the constraints imposed on the crewman by the mission environment.

5. Backup support systems and/or redundant systems necessary to assure performance of critical functions during the M&R cycles.

6. Maintainable systems are designed to facilitate the maintenance and/or repair of those functions identified as potential weak links.

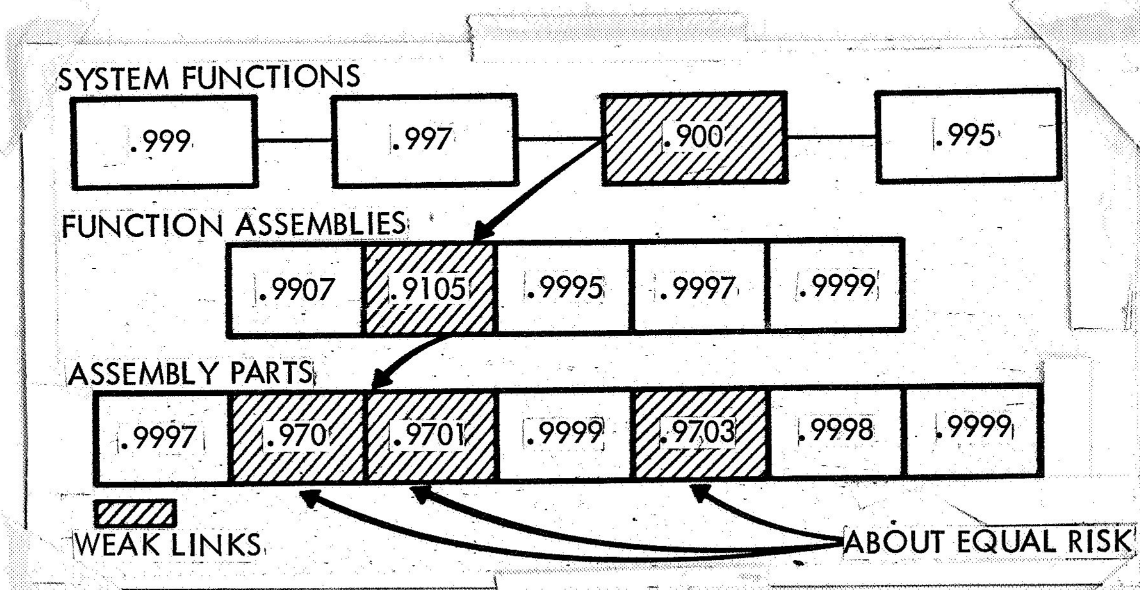


Figure 1.5 Weak Link Analysis

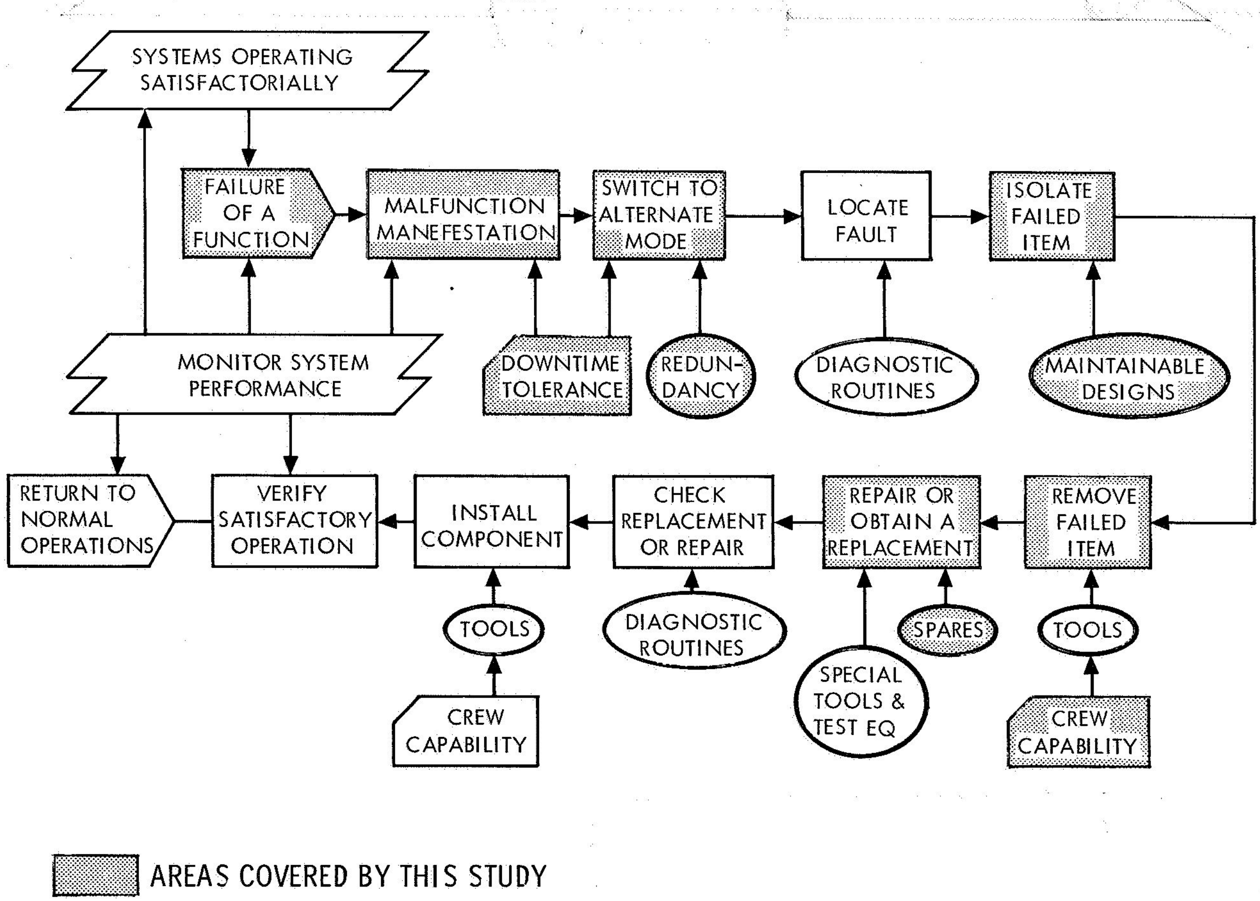


Figure 1.6 Failure and Correction - Analytical Logic

1.6 THE STUDY APPROACH

The study was conducted as indicated by the logic of Figure 1.7. The data from the SD study, "Manned Planetary Flyby Missions Based on Saturn/Apollo Systems," provided the baseline mission and system description down to the conceptual level. This study selected specific hardware. select specific hardware.

Midway through this study it became apparent that, in order to perform the proposed analysis to the level of depth necessary for meaningful results, it would be necessary to define the systems design to the point where specific hardware could be identified. To accomplish this task within the scope of the study, it was decided that subcontractors who were known to be expert in the individual fields should be solicited for support. The following subcontractors, who agreed to participate by defining and analyzing the system functions as listed, provided gratifying results. Each was provided a suggested statement of work along the lines indicated in the study logic and performed the study at their expense excepting as noted:

1.	A. C. Electronics	-	Guidance and Navigation
2.	Aerojet General	-	Propulsion Engines
3.	AiResearch*	-	Environment Control and Life Support
4.	Allison Division of G. M.	-	Propellant Tankage
5.	Atomics International**	-	Electrical Power Source
6.	Bell Aerosystems	-	Positive Expulsion Tankage
7.	Collins Radio Corp	-	Communications, Voice and Telemetry
8.	Dalmo Victor Corp	-	Deep Space and Probe Com. Antenna
9.	Eagle-Pitcher	-	Earth Entry and Peaking Batteries
10.	General Time Corp	-	Central Timing Equipment
11.	Honeywell Corp	-	Attitude, Stability and Spin/Despin Control
12.	Marquardt Corp	-	Reaction Control and Spinup/Despin Engines
13.	Motorola Inc	-	Up Data Link
14.	Raytheon Mfg Company	-	Guidance Computer
15.	Simmonds	-	Propellant Gaging

*Taken from several funded studies, plus consultation.
**Taken from a former funded study.

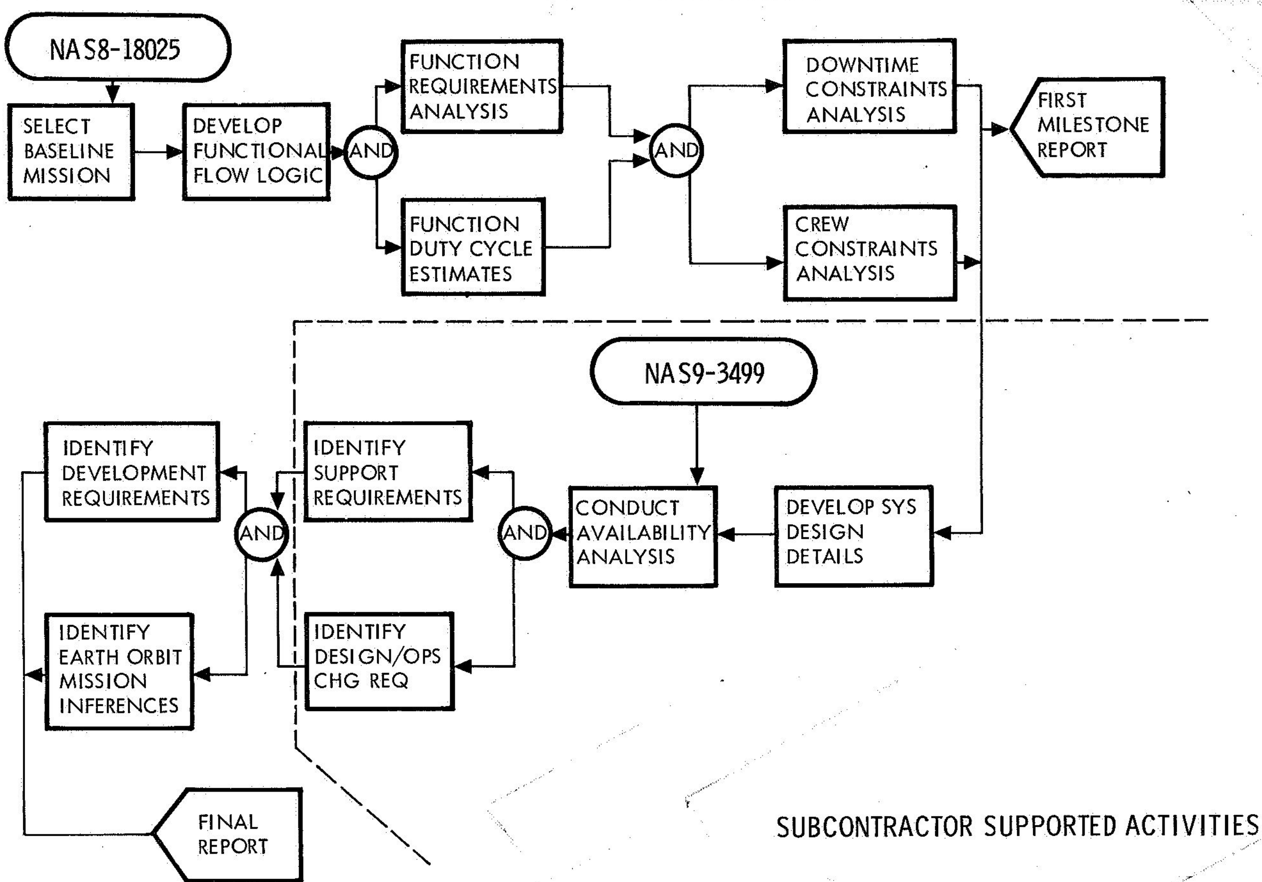


Figure 1.7 Study Logic Mission Durations Extension Studies

2.0 THE EXTENDED MISSION CHARACTERISTICS AND COMMONALITIES

2.1 THE BASELINE PLANETARY MISSION

The baseline mission selected for this study was taken from one of the candidate missions identified in the previously referenced study (NAS8-18025). It involves a 1977 departure date for a single planet flyby of Mars. The top level functional flow is presented in Figure 2.1 along with the second level for selected mission phases and their respective duration. Although this may not be the actual mission finally selected, it includes all of the characteristics and functional requirements of any near planet missions exclusive of the scientific objectives.

The study of mission characteristics and requirements indicated that the missions vary only in the length of specific phases and the number of times a phase is repeated. Therefore, if the baseline mission includes all the potential types of phases and they are as long or longer than the selected mission, the resulting requirements and constraints identified will, for the most part, represent "worse case" situations. Such is the case with the selected baseline.

Artificial gravity was assumed to be a requirement for the long trans-planet/transearth coast periods because it imposed the requirement for additional system functions and reduced the duty cycle requirement on key system functions. For additional arguments for the artificial gravity mode, based on system/missions effectiveness, see Volume III of this report. The artificial gravity mode is justified on the basis of the measurable improvement in crew safety possible and the resultant reduction in crew work load and energy consumption.

2.2 THE BASELINE SPACECRAFT

The spacecraft used for the study baseline is presented in Figures 2.2 and 2.3. It was taken from the NAS8-18025 study. The detailed subsystem descriptions were derived by the participating subcontractors and NR/SD using Apollo/AAP derivations. In each case specific system hardware was identified to fulfill the required functional requirements. For details, see Volume III and the references therein,of particular interest is the following:

The Environment Control and Life Support System included both storable O_2, under high pressure and cryogenics conditions, and a Bosch Reactor/Electrolysis Cell as a backup/O_2 recovery system. The electrical power

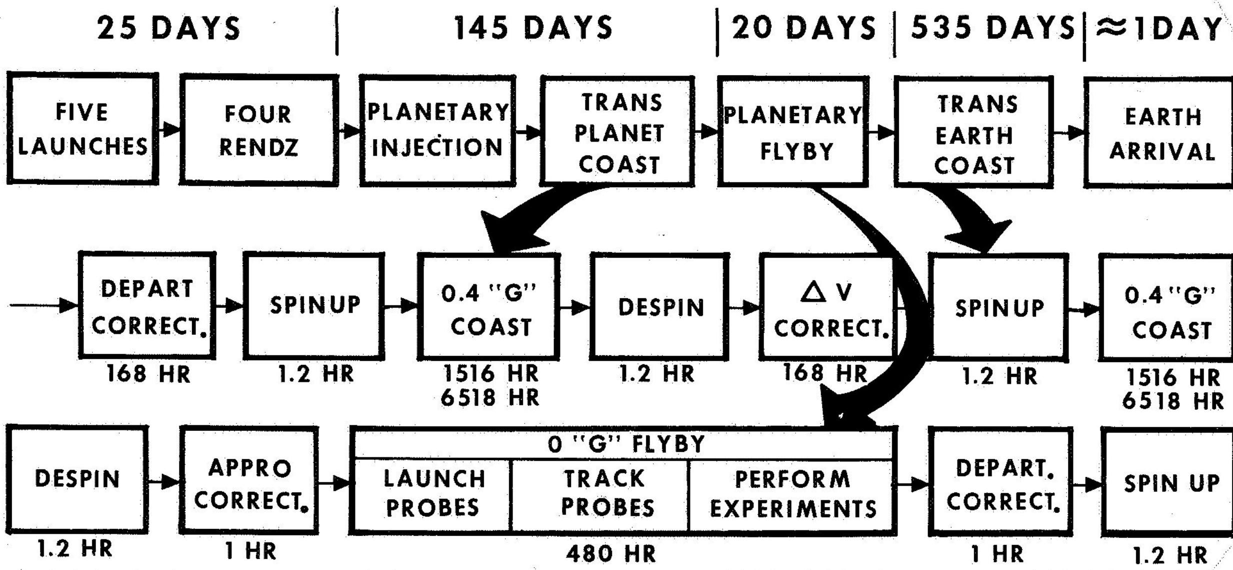


Figure 2.1 Baseline Mission Functional Flow Logic

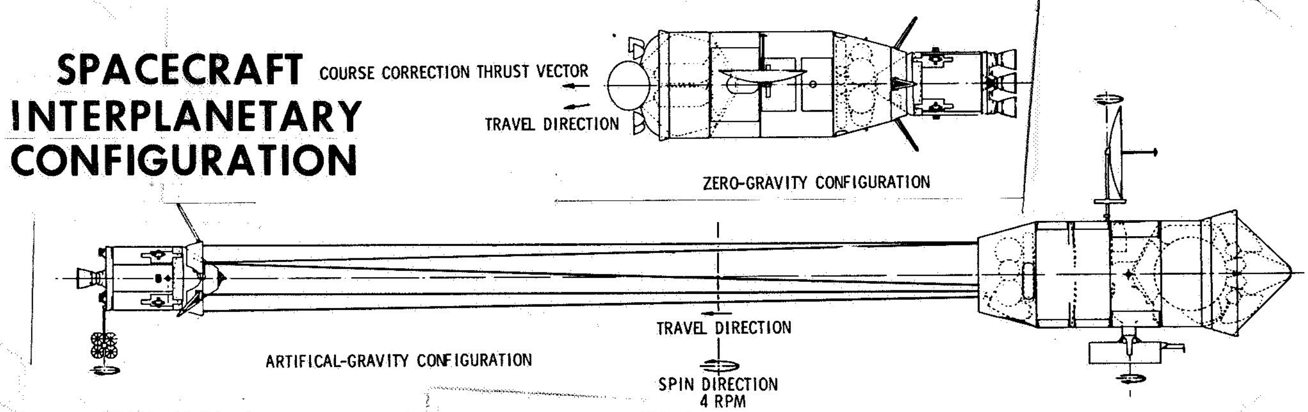


Figure 2.2 Spacecraft Interplanetary Configuration

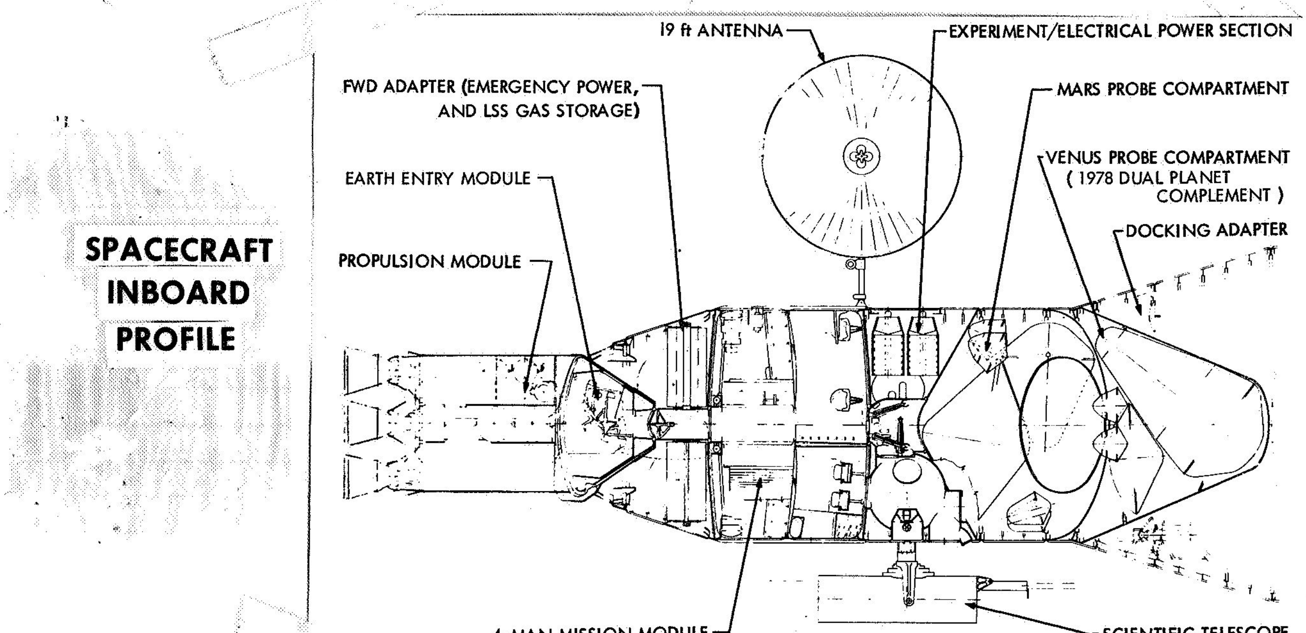


Figure 2.3 Spacecraft Inboard Profile

system included an Isotope-Organic Rankine as the primary source with an Isotope Thermoelectric backup with batteries for peaking and earth entry. The stability control was similar to Apollo. The spin control and engine functions used Apollo components. The G&N was assumed to be the Apollo system with earth control as the primary mode, except during planet flyby. The communication system was assumed to be Apollo with the addition of higher data capability, a 500-watt amplifier and a 19-foot dish to the existing antenna. Other functions such as the Apollo Up-Data Link, Fuel Tanks, and the Central Timing Equipment, were found to be adequate. The midcourse propulsion was assumed to be provided by three Apollo/LEM engines.

2.3 EARTH ORBITAL PLANETARY MISSION COMMONALITIES

Because of the increased interest in extended earth orbital missions, it is essential to show the relationships between the requirements for extended lunar, planetary, and the earth orbital missions. For this reason, and to demonstrate the applicability of this study results to all types of extended space missions, it is desirable to review the characteristics of these missions and establish points of Commonality.

Figure 2.4 presents, in functional flow, the operations required to perform either an earth orbital mission, or the baseline planetary flyby. The AAP Earth Orbit (E.O.) missions provided the E.O. data. The first level is general enough to describe both mission classes. Differences in the first three phases are minor except for the number of launches or rendezvous required, resulting in the same functional requirements for both missions. At the second level, where differences may be expected to appear, there is a startling similarity in both the operations for a given phase and resultant subsystem functional requirements. During the preliminary earth orbital phase, both missions require checkout in orbit, both make velocity changes — the difference being only in the direction and magnitude of the vector. Therefore, the resultant functional requirements are the same. During the mission operations phase both have long periods of inactive coasts interrupted by velocity corrections; again, the differences exist only in the duration of these coast periods and the magnitude of the velocity vectors.

The major differences in the two mission classes exist in the planet flyby period where probes are launched and recovered, or in the earth orbit resupply operations. The planet flyby is very similar in nature to any coast period except for the high degree of scientific support activity. However, this has little effect on crew safety. The earth orbital resupply operations constitute the only different type of operation. But, even there, it is equivalent to an additional rendezvous operation which was required in the earlier phases of the planetary missions and no new functional requirements added.

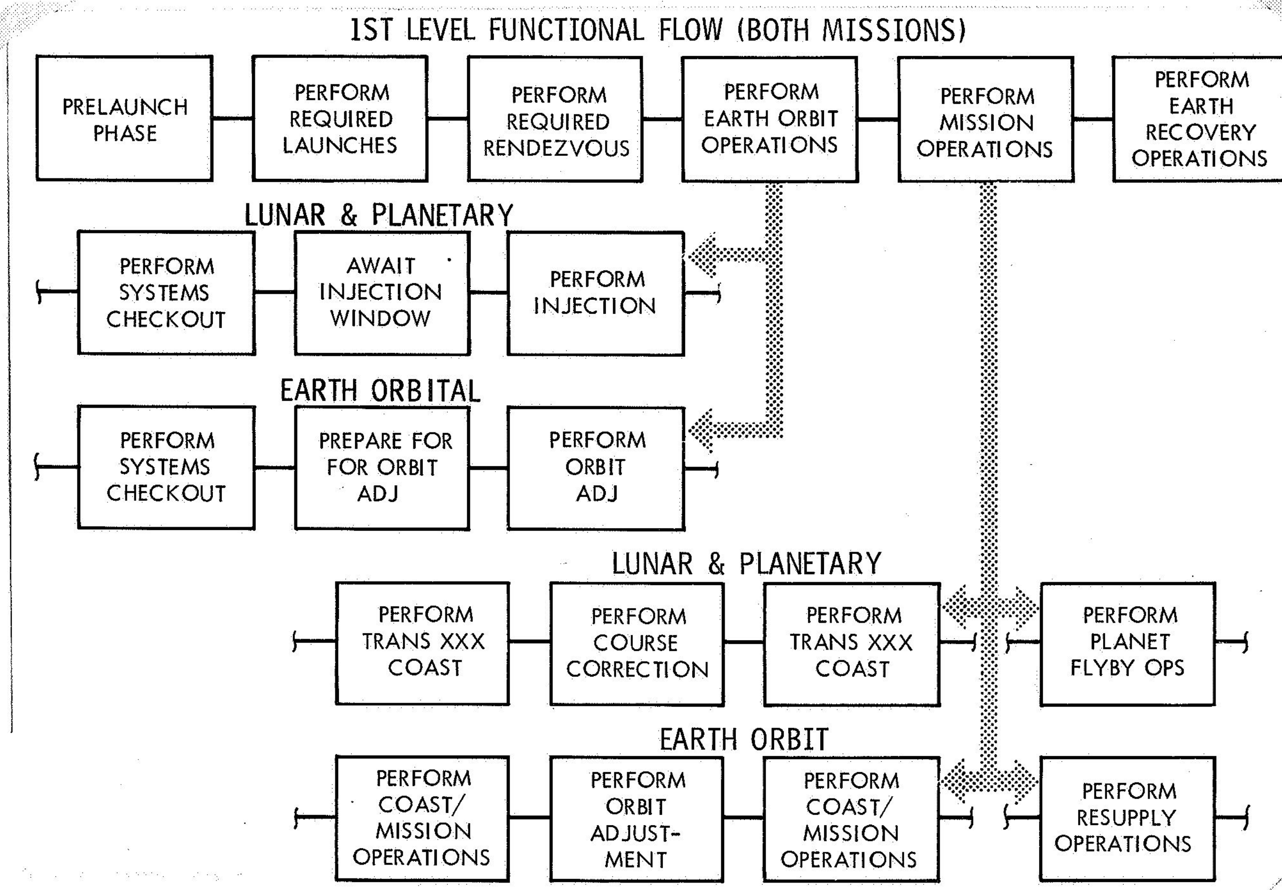


Figure 2.4 Planetary - Lunar and Earth Orbit Mission Commonality - First Level Functional Flow (Both Missions)

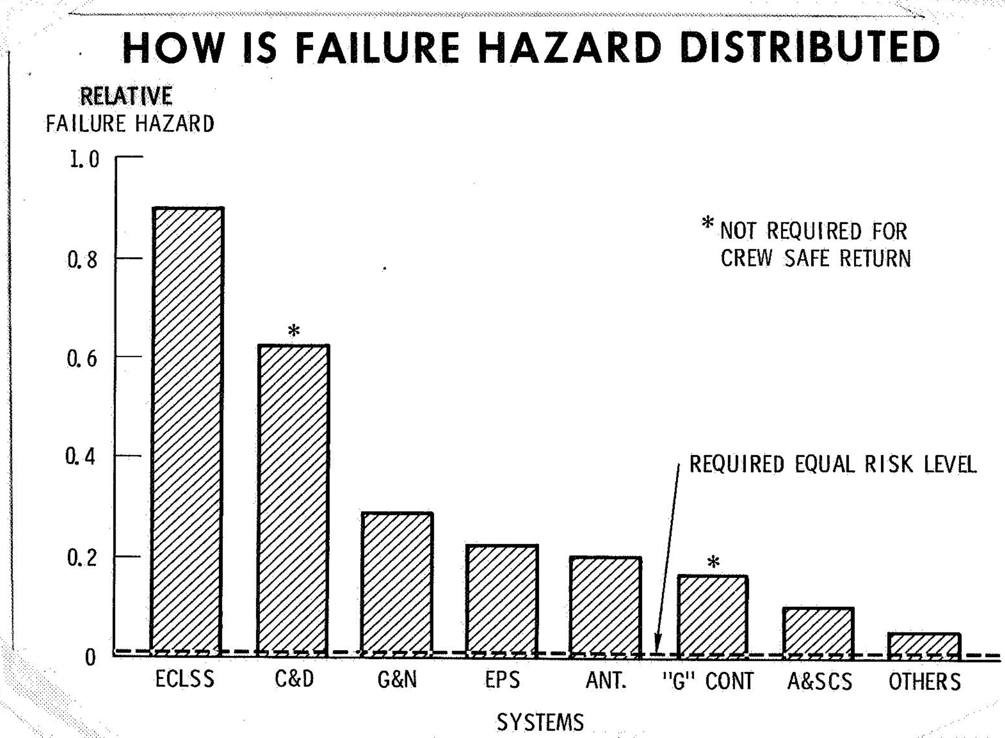


Figure 2.5 Failure Hazard Distribution

The results of the commonality analysis indicate that there are few differences in the earth orbital and lunar/planetary flyby missions as they affect the mission system functional requirements. These differences are manifest in the form of the length of a given operation, and where the functions are to be located, i.e., with respect to the space station or, the logistic vehicle in the one case, and with respect to the Mission Module or the Reentry module, in the other case.

2.4 UNDERSTANDING RELIABILITY AND CREW SAFETY OBJECTIVES

The so-called "numbers" game which has of late been associated with the field of reliability has lead to a lack of understanding and disbelief in reliability estimates, in general. To state that a mission has a reliability of 0.90 means nothing unless it is made clear what factors are contained in the logic which permitted the assessment. The fact that a failure occurs does not mean that the mission was unsuccessful; for example, all the Mercury missions encountered failures but none were considered unsuccessful, or even unreliable. In fact, all were evaluated as highly successful.

For this reason NR/SD has elected to use the Probability of Crew Safe Return (P_S) as the primary measure of reliability. This indicates the probability of the crew returning safely to earth. The results of applying this criteria to a space mission is perhaps surprising because some functions that were formerly considered critical were found to not actually affect P_S. Such functions as communications could honestly be considered less critical. As a result of this situation, SD established three criticality classes into which the different spacecraft functions were separated to facilitate an understanding of what is inferred by the safety/success assessments.

The classification is based on the criticality of the function as follows:

Criticality I applies to those functions and components directly affecting the crew safe return (P_S).

Criticality II applies to those functions and components not required to achieve P_R, but are required to accomplish the mission in the manner prescribed. These were called "crew comfort" functions; communications and artificial gravity are examples.

Criticality III applies to those functions associated with obtaining and processing the scientific data, and are not required for the first two classes. This class was not evaluated during this study.

2.5 THE EXTENDED MISSION SYSTEM WEAKNESSES

The baseline mission systems requirement analysis revealed that some systems had to operate nearly one hundred percent of the time while others operated as low as five percent of the time. See Table 2.1.

The result of imposing the duty cycle requirements on the baseline mission system which are made up of contemporary data is reflected in the bar graph of Figure 2.5. From this, the systems that contribute the highest failure hazard, and therefore those requiring the most attention during the analysis, can be identified. It is also evident that all of the systems will contribute an unacceptable failure potential. Further, since it was an objective of this study to equalize the hazard of failure at a acceptably low level, it is evident that support requirements will have to be distributed between the systems in proportion to the bars.

Table 2-1. System Duty-Cycle Requirement for a Manned Planetary Mission

Function	Duty-Cycle Estimates*	
Guidance and navigation	5%	800 hours
Communications	10 to 30%	≤4,800 hours
Stability control	6%	960 hours
Propulsion motor	≤ > cycles	
"G" control engines	16 to 20 cycles	
Life support	100%	16,000 hours
Environmental control	100%	16,000 hours
Electrical power system	100%	16,000 hours

*Based on a typical Mars flyby mission

3.0 THE EXTENDED MISSION CONSTRAINTS

3.1 MAINTENANCE TIME CONSTRAINTS

Mission requirements and constraints stem from the need to support both man and mission commitments as indicated in Figure 3.1. When these functions become inoperative, either the crew and/or the mission commitments are endangered. However, there is a time differential between the failure occurrence and the non-reversible emergency situation; these form maintenance time constraints. Maintenance or repair action is effective only so long as the mission can continue safely without the function, or if a backup function (or system) is available for use during the repair action.

It is logical to assume that the function is required during some specific part of the mission, or a percentage of the total duration, perhaps randomly distributed throughout the mission. Also, it is just as logical to assume that the mission can proceed in a degraded mode, though perhaps only for a short period of time. If this is true, that period can be used for both periodic maintenance and the unscheduled repair or replacement actions. The downtime constraint is therefore defined as:

> A restriction imposed on the total allowable elapsed time that a mission system function can be out of service before a situation is created that would result in ultimate loss of the mission spacecraft and/or crew.

It should be recognized that downtime constraints are not always described by a single value defining an all-black or all-white situation. Crew or function degradation may be gradual as in the case of CO_2 buildup. Or, almost instantaneous, as would be the case at rapid decompression.

Figure 3.2 presents the results of CO_2 systems removal function failure as a function of downtime. Note that there is at least 140 hours of safe downtime for the four-man crew with 700 ft^3 of free volume in the cabin.

four

The results of the system function downtime constraints analysis is summarized in Table 3.1. Note that most functions can be down for over 24 hours. Few are sensitive at very specific time periods only (perigee corrections and earth entry). Most of the other situations could be circumvented by some design action such as a redundant function.

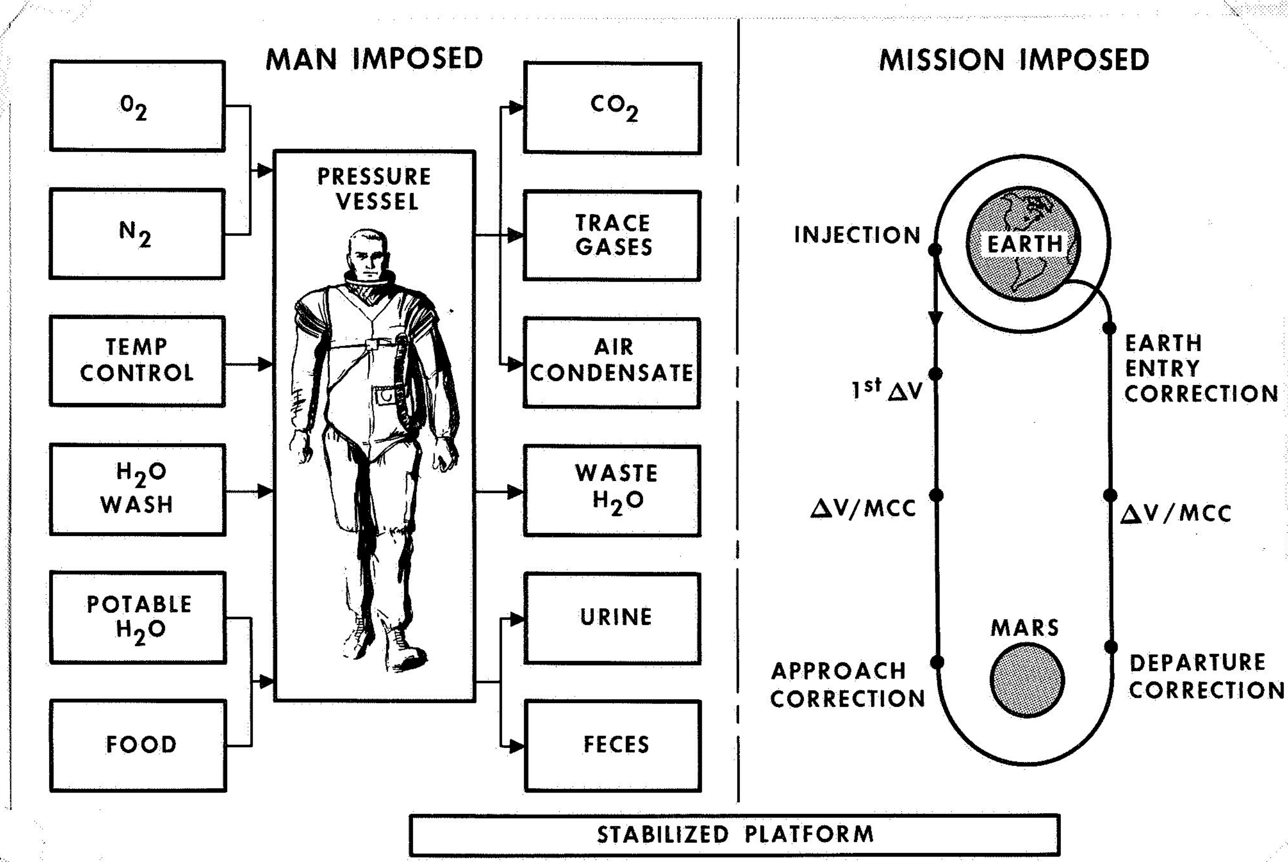


Figure 3.1 Sources of Requirements and Constraints

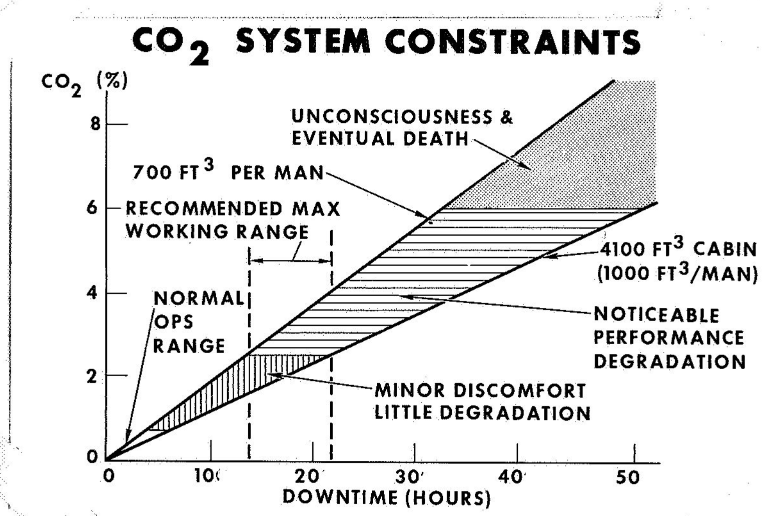


Figure 3.2 How is Failure Hazard Distributed

Table 3-1. Planetary Mission System Downtime Constraints

System, Function	Downtime Constraint (hr)	Causation and Remarks
Stability control	0.2	Required to neutralize worse-case spinup.
	Over 24 (repairs)	Repair time limited only by mission-profile commitments.
Attitude control	7 at perigee (planet) 15 at earth arrival Over 24 otherwise	Limited by mission-profile commitments.
Velocity control	Same as above Most of mission	Limited by mission-profile commitments.
	0.3 at earth arrival	Earth-arrival retro; must be made within a narrow time frame.
Atmospheric pressure	0.1 to 0.3	Assumes meteoroid puncture of 1 inch or greater; risk is less than 1/100.
	Over 24	Other causations.
Oxygen	120 to 210	Metabolic consumption and leakage; depends on cabin size.
Nitrogen	1300 to ∞	Can operate without it.
Carbon-dioxide removal	20 to 40 or greater	Crew tolerance limits build up but increase only results in reduced efficiency until about 40 hours; depends on cabin size.
Cabin temperature	2 to 4 minimum	Depends on cabin size, equipment operating, position and attitude with relation to sun, and the thermal inertia of the spacecraft.
Isotope temperature	1.2	Coolant required to stabilize isotope temperature; loss of control will result in loss of power and radiation contamination.
Cabin humidity	1.8 to 3.0 minimum	100-percent humidity will result in condensate on cold surfaces, eventual electrical shorts, and corrosion of critical elements.
Communication	No practical limit	Not required except for primary guidance and navigation data sometime during midcourse and prior to planet arrival.
Guidance or navigation	No limit - during midcourse	Earth support primary most of the time as long as communication system functions.
	7.0 at planet	Required to facilitate accurate velocity correction.
	0.3 at earth arrival	Required to facilitate acquisition of entry corridor.
Water supply	Over 24	Proper temperature control can extend this considerably.
Food supply	Over 720	Rationing of any form can extend this indefinitely.

The data clearly indicates that adequate time is available to perform required maintenance actions and there probably is no critical situations.

3.2 CREW CONSTRAINTS

The crew imposes constraints on the mission systems design due to the result of their ability or inability to perform useful work in the projected situation. These constraints take the form of maintenance time requirements, force producing capability and the associated metabolic costs.

Time requirements come from the active repair time required by a crewman to perform a given task. As indicated by Figure 3.3A, the study showed that 95 percent of the projected tasks could probably be performed in less than two hours, under normal working conditions. This must be modified by the effects of working condition impediments such as those assessed in Figure 3.3B. Note that under EVA conditions the 95 percentile could be nearer to six hours.

Force producing capability was found to vary considerably as a function of working conditions. As indicated by Figure 3.4, his ability to produce a translatory force drops rapidly as the work area becomes more awkward to reach; zero g reduces his capability even more. If unrestrained, the worker must use one hand to neutralize the force vector acting on his body; if restrained, the inefficiencies of the harness/ anchor point reduce his capability. The effects of reduced gravity and/or body plus equipment mass seem to affect the worker output as measured in horsepower (HP). Figure 3.5 indicates that the HP could easily be reduced to 50 percent of his normal capability to compensate for Newton's second law. In any event, the remaining force producing capability seems adequate to perform a properly planned repair.

Work Costs are manifest in the form of an increase in O_2 consumption and CO_2 output. As indicated by Figure 3.6, these could easily increase to 200 percent under zero g, imposing a heavier load on the atmospheric control functions.

3.3 MAINTAINABILITY CONSTRAINTS

The ability to repair and maintain a system depends, in large measure, on the design. In Figure 3.3, a log-normal curve was presented as depicting the distribution of time required to perform the expected maintenance actions. The mean time to repair (MTTR) was actually near to 14 minutes. These data were not taken from a maintainable design. As indicated by the data of Figure 3.7, it has been shown that active maintenance time could be reduced to less than half through packaging for maintenance. An example of such a design is presented by one Apollo Component shown in Figure 3.8.

CREW CONSTRAINTS

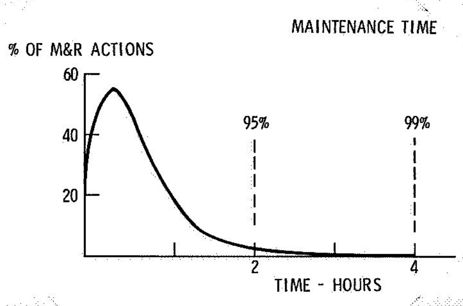


Figure 3.3A Maintenance Time, Estimated Repair Time Distribution (Active)

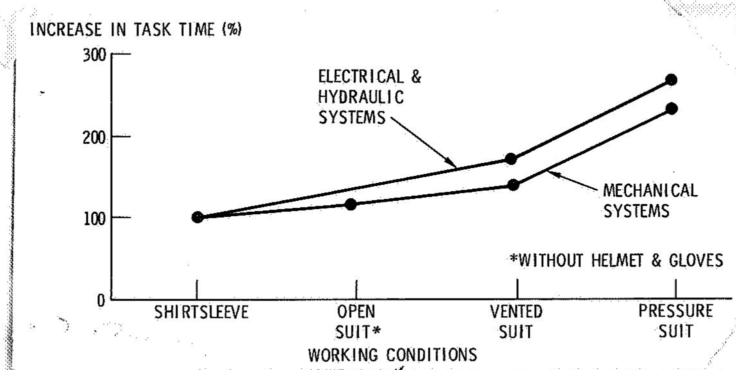


Figure 3.3B Maintenance Time, Crew Working Condition Constraints

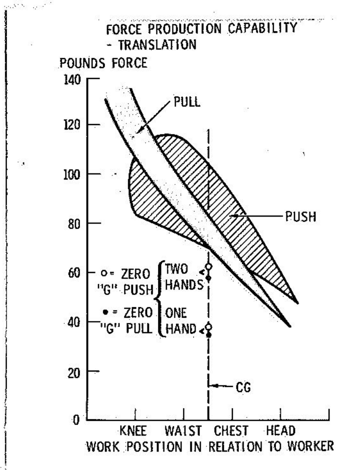


Figure 3.4 Crewmen Producing Translational Forces

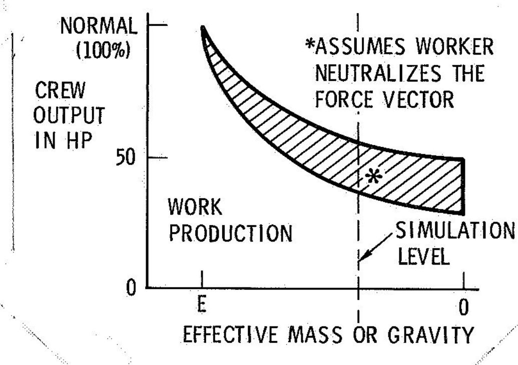


Figure 3.5 Crew Work Production

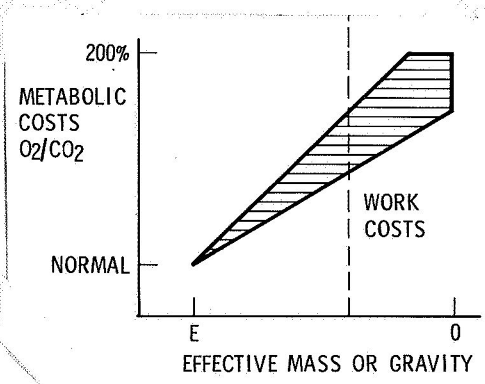


Figure 3.6 Metabolic Costs of Work Production

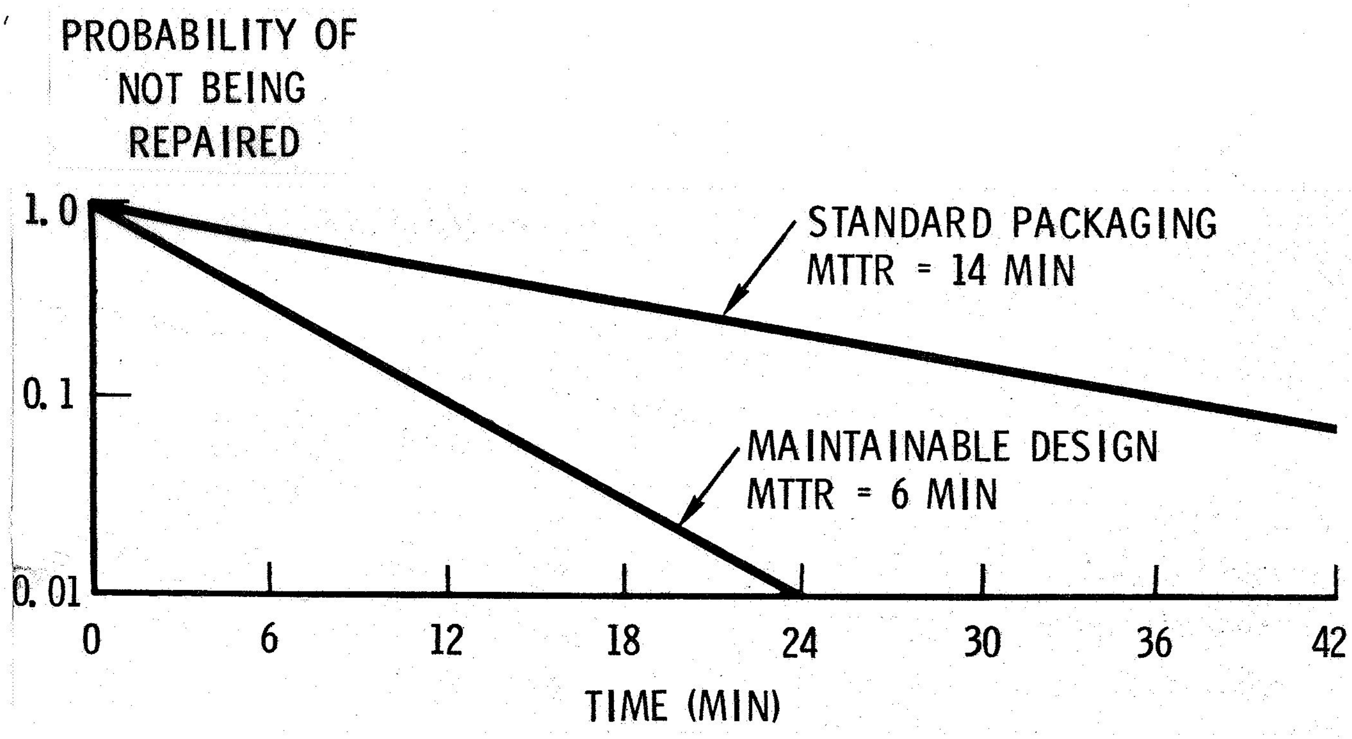


Figure 3.7 The Maintainability Constraint

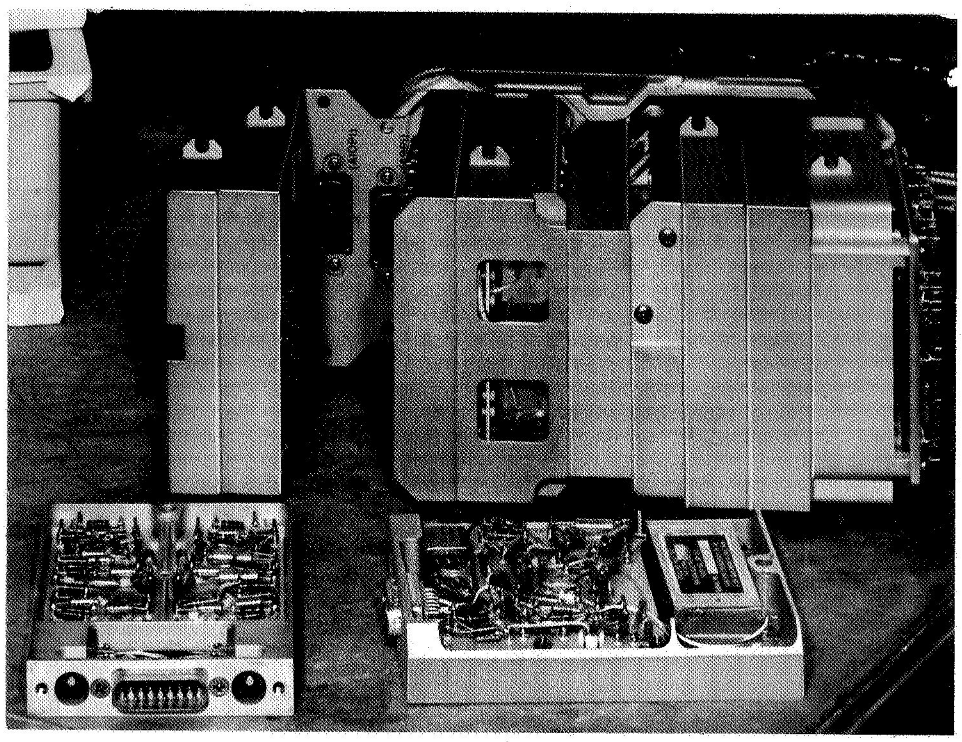


Figure 3.8 Apollo Premodulation Processor, Open, to Show the Modular Design

4.0 THE EXTENDED MISSION IMPLICATIONS

4.1 THE ANALYTICAL TECHNIQUE APPLIED

It has been established that systems will probably fail and that repair is both necessary and possible. However, maintenance may not be the only solution, and indeed, is not expected to be the single solution. The availability concept has been shown to be an effective way of resolving the potential problems, and during this study, each subcontractor applied the concept to his respective system to demonstrate its application and to determine the resultant requirements.

Detailed logic for the analysis is presented and explained in Section 1.5. It may be summarized and its application illustrated by Figure 4.1. In this example, the Space Radiator was one potential weak link. It was impractical to repair but could be resolved by dividing it into six sections, any four of which will handle the expected load. The Cabin Temperature Control was spared because it could easily be replaced by removing four screws and an Amphenol connector. The Space Radiator Outlet Check Valve was made redundant because of the time constraint on the coolant loop.

The same approach was used on all the subsystems. The objective of each action recommended was to reduce the risk of a non-repairable failure to an acceptable level and to equalize the probability associated with each component within the function so that there were no "built-in" weakness that could not be compensated for by a maintenance action.

Another example is presented in Figure 4.2, the Attitude and Stability Control System (A&SCS). The top level reliability logic indicates that the Attitude Hold - Vehicle Maneuver function is the only weak link. It was evaluated as to potential operational concepts and through weak link analysis. The artificial g/zero g combination was found to be a more reliable concept although they could be made equal at the expense of 37 additional repair actions for the 0 "g" mission. The second level logic indicates that the automatic mode is weakest. From Figure 4.3, the causes and recommended corrections can be identified. Replacement at the module level is recommended because of the lower weight penalty and higher P_S. All weakness could be corrected through maintenance.

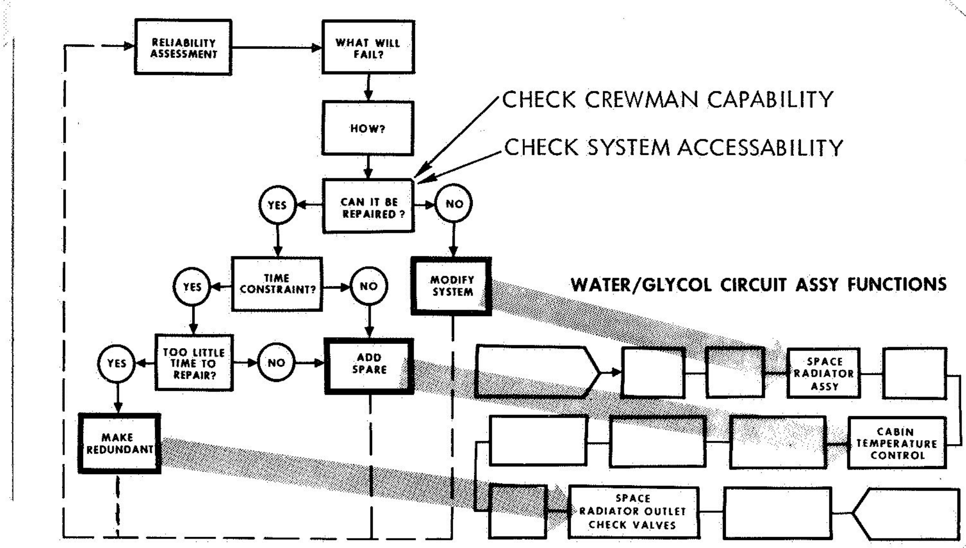


Figure 4.1 The Logic of Availability Analysis and Design for Maintenance

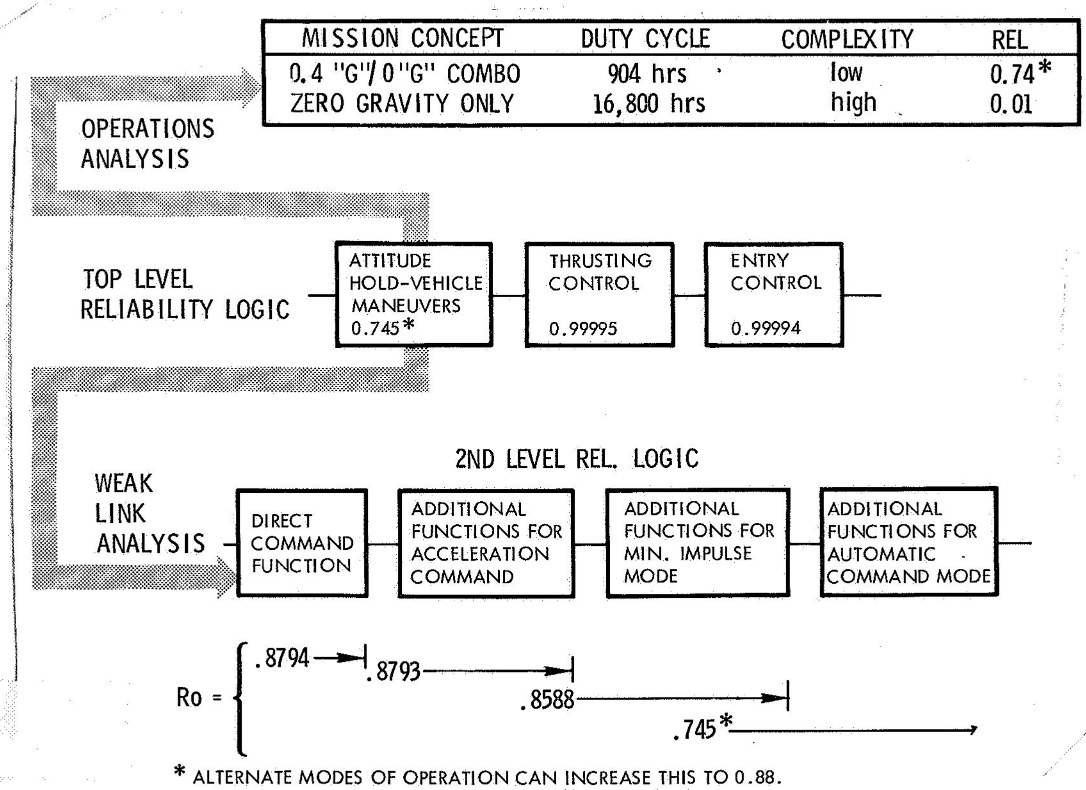


Figure 4.2 Attitude and Stability Control - Problem Analysis

4.2 BASELINE MISSION IMPLICATIONS

In determining the baseline mission implications, each subcontractor designed a system which would meet the functional requirements using contemporary hardware, using Apollo where possible; then proceeded with the analysis. Details are presented in Section 4 of Volume III. A summary of the resulting support requirements is presented in Table 4.1 and 4.2. They indicate that to perform the baseline mission in the manner prescribed:

1. The probability of safe return could exceed 0.993.

2. Only about 908 pounds of spares may be required.

3. No more than 258 unscheduled maintenance actions are expected.

4. The minimum system availability will probably exceed 0.9996.
5. Some design implications were involved:

Design actions, over and above those planned from an Apollo/AAP spacecraft were required. Some of the more important are listed briefly in Table 4.3 and elaborated in detail in Volume III.

4.3 EARTH ORBITAL MISSIONS IMPLICATIONS

In paragraph 2.3, the commonalities between earth orbit mission (EO) requirements and the baseline planetary mission were established. Briefly, they have common functional requirements, varying only in the duration of specific phases. Therefore, choice of the two-year baseline mission used herein embodies most, or all of the critical functions required for an EO mission. However, since there are two distinct operations associated with the space station, these must be considered in the application of the foregoing data.

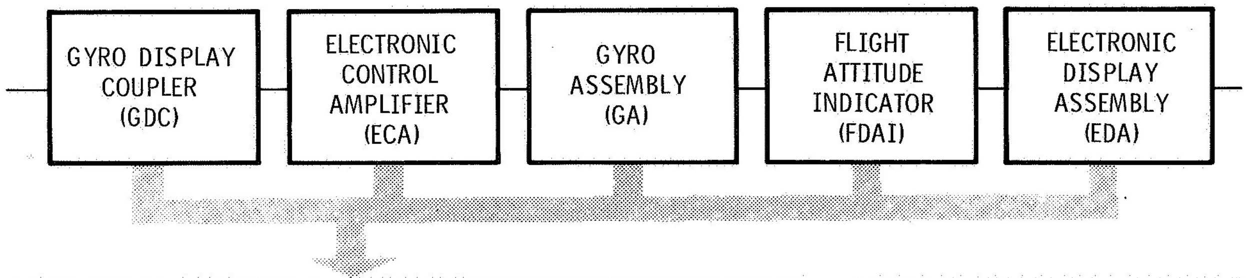
Figure 4.4 presents the distribution of required functions between the space station and the logistic vehicle. This concept results from a NR/SD design study of an orbiting space station. The recommended operational concept involved the launch of the space station, unmanned, and a separate launch of the logistic vehicle every 90 days thereafter. The logistic vehicle remained docked at the space station throughout the 90-day period, making any velocity vector corrections required. Under that concept, the functional logic of Figure 4.4 applies and the system support requirements are estimated to be as presented in Table 4.3. These data indicate that for the space station:

1. The probability of safe return can exceed 0.99976.

2. The probability of no abort can exceed 0.996.

2ND LEVEL, ATTITUDE HOLD - VEHICLE MANEUVER FUNCTION

RELIABILITY LOGIC



SUB FUNCTIONS	R_O	BLACK BOX LEVEL			MODULE LEVEL		
		P_S	SPARES	WEIGHT-LB	P_S	SPARES	WEIGHT-LB
1. GDC	.887	.993	2	49.4	.998	4	12.2
2. ECA	.976	.9995	1	16.1	.9999	6	4.1
3. GYRO ASSEMBLY	.990	.995	1	22.5	.995	1	7.0
4. FDIA	.994	.9998	1	8.9	.9997	1	8.9
5. EDA			1	24.8		1	7.5
SYSTEM TOTAL	.76	.992*	6	121.7	.997*	13	39.7

P_S = CONTRIBUTION TO PROBABILITY OF SAFE RETURN

*BACKUP MODES INCREASE THIS VALUE TO OVER .9994

Figure 4.3 Attitude and Stability - Availability Analysis

EARTH ORBITING SPACE STATION FUNCTIONS

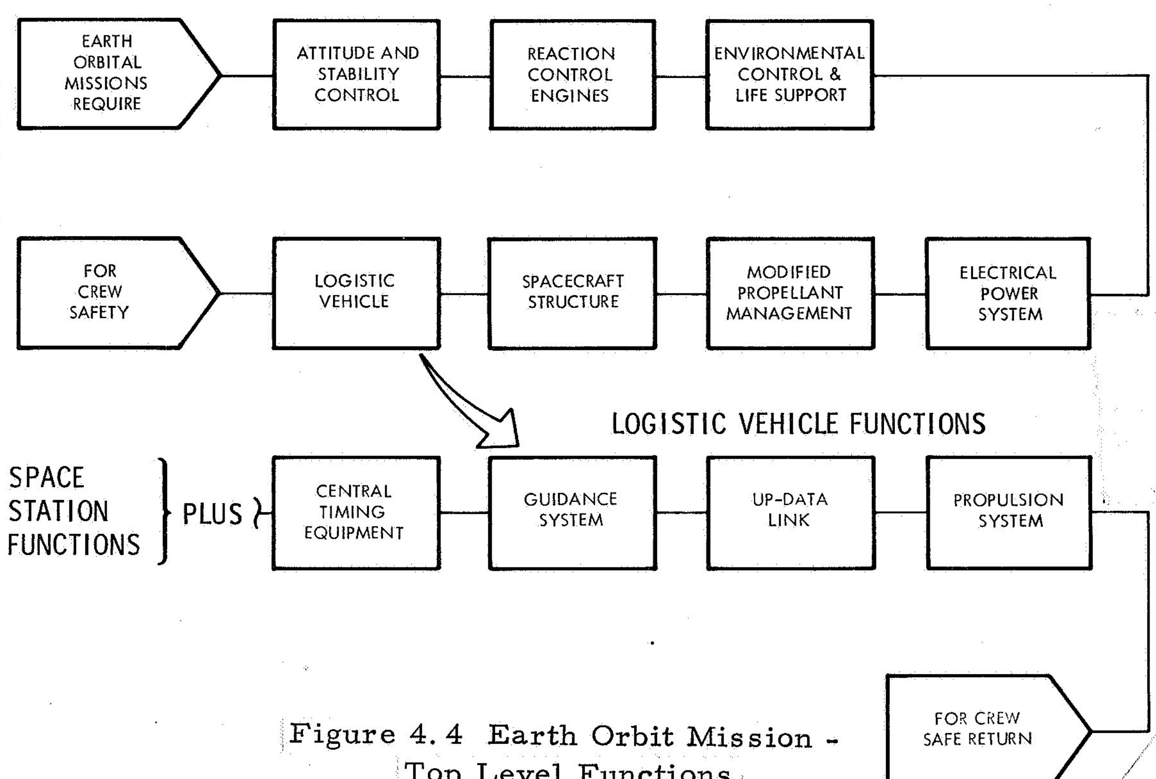


Figure 4.4 Earth Orbit Mission - Top Level Functions

Table 4.1. Crew Sensitive Systems Summary (Criticality I)

Section No.	Spacecraft System	Reliability	Spares Required	Contribution to P_s	Spares Weight (lb)	Status*
4.2	Attitude and stability control system	0.879	13	0.997	39.6	Qualified
4.3	Reaction control engine	0.99975	0	0.99975	0	Qualified
4.8	Guidance and navigation	0.7195	44	0.998	137.2	80-percent qualified
4.1	Environmental control and life support	0.104	85	0.9991	165.0	70-percent qualified
4.6	Propulsion system	0.996	0	0.99999**	0	95-percent qualified
4.5	Propellant management	0.989	0	0.999999**	0	85-percent qualified
4.9	Electrical power	0.788	17	0.9995**	103	50-percent qualified
4.10	Central timing	0.978	4	0.999993	8.3	Qualified
4.4	Updata link	0.994	4	0.999	5.0	Qualified
	Structure	0.999999	0	0.999999**	0	Qualified
	Criticality I Totals	0.05	167	0.993	458.1	

*Except for life tests

**Design Redundancy can vary achieved values, see Table 4.3.

41

Table 4.2. Crew Comfort Sensitive Systems Summary (Criticality II)

Report Section	Spacecraft Systems	Reliability	Spares Required	Contribution to P_s	Spares Weight (lb)	Status*
4.1	ECLSS/O_2 recovery	0.90	18	0.9993	48.6	Unqualified
5.1	Gravity control	0.83	4	0.999	28.2	50-percent qualified
5.2	Communications (MM)	0.38	14	0.99	78.0	90-percent qualified
5.2	Communication (EEM)	0.99	0	0.99	0	Qualified
5.3	Antenna	0.81	41	0.994	3.0	70-percent qualified
5.4	Extension/Retraction	0.9998	0	0.9998	0	Unqualified
4.9	P/O Electrical Power	0.787	14	0.9995	292	Qualified
	Criticality II Totals	0.18	91	0.973	449.8	

*Except for life tests.

Table 4.3. Design Implications

System	Design Implications
1. Propulsion	Three-engine configuration Common thrust structure 2 of 3 normally operative Redundant pressurant function Pressure relief during non-use* Purge lines and engine after usage*
2. Electrical Power	Isotope power source recommended Redundant CRU loops recommended Backup cascade thermoelectric power recommended Redundant cooling required*
3. Artificial Gravity Systems	Redundant cable-drum and motor required Jettison malfunctioning retraction components Provide for powered rendezvous as a backup concept*
4. Communications Systems	Develop Passive Antenna System* Develop High Power TWT's
5. Structure	Meteoroid necessitates use of multilayer design and four pounds per foot^2 as average density of skin
6. Maintenance Concept	Design for M&R at Module/subassembly level Fault Isolation to parallel maintenance concept* Minimize test points
7. ECLSS	Multi-loop Space Radiator Design Required Redundant water Recovery Loop Backup CO_2 Reduction (Bosch System)

*Recommended concept, not required to meet objectives

3. Only 680 pounds of spares may be required for a full two-year mission, i.e., no resupply required for critical functions.

4. There may be no more than 192 unscheduled maintenance actions.

5. The minimum systems availability will probably exceed 0.9997.

Table 4.4. Earth Orbiting Spacestation, Support Requirements for Crew Safety

Spacestation System	Reliability (2 yr)	Spares Required (2-yr total)	Contribution to P_s	Spares Weight (lb)	Status
1. Attitude and stability control system	0.879	13	0.997	39.6	Qualified
2. Reaction control engines	0.99975	0	0.99975	0	Qualified
3. Environmental control and life support	0.104	85	0.9991	165	80-percent qualified
4. Propellant management	0.989	0	0.999999	0	90-percent qualified
5. Electrical power	0.978	17	0.9995	103	50-percent qualified
Criticality I (P_s)		115		307.6	—
6. Communications	0.38	14	0.99	78	90-percent qualified
7. Antenna Systems	0.99	41	0.999999	3	Qualified
8. P/O Electrical Power	0.787	14	0.9995	292	Qualified
Criticality II		170		680	—

These reductions in support requirements and increase in P_S are due to the logistic vehicle carrying many of the high failure systems and only operating for a 90-day period.

4.4 DEVELOPMENT PROGRAM IMPLICATIONS

The results of the study in general indicate that:

1. Contemporary hardware (Apollo/AAP level technology) can fulfill most of the system functional requirements.

2. Relatively minor modifications may be required to achieve the desired maintainability.

3. Repackaging, in some cases, is required to assure accessibility to components scheduled for maintenance.

As indicated in Tables 4.2, 4.3, and 4.4, most of the systems are nearly qualified at the function level; the remaining test requirements involve life demonstrations to meet the new mission duration. Some functions, such as the propulsion engines, are required to operate for less than the qualified time on the planetary and earth orbit missions. However, these components require test to demonstrate their capability to withstand the long, deep-space exposure - for planetary missions only.

Some of the major development programs required are:

1. Cabin temperature/humidity control physics

2. Carbon dioxide control

3. Cabin atmospheric control and O_2 regeneration

4. Water/Urine recovery

5. Electrical Power Source - a combined Isotope Organic Rankine cycle with a Thermoelectric system to provide emergency power. This combination seems the most desirable from a reliability/ safety point of view. To support this system, these functions must be developed:

    a. High temperature loops

    b. Combined Rotating Units

    c. Isotope sources

6. Artificial gravity physics

Some development programs recommended to improve performance but not necessarily required, involve:

1. High-gain antenna - passive
2. Gyros - particularly for stable platforms and momentum exchange control systems
3. Microelectronics for use in communications, data, and control functions

4.5 EVA IMPLICATIONS

Since the study was devoted to an analysis of all potential system failures, inherent within them are those requiring extra-vehicular activity to accomplish the identified maintenances and repair action. A concerted effort was made to minimize these; however, a few remain as possible but very remotely so. As indicated by Table 4.5 where the potential tasks are listed, the cumulative chance is less than 2×10^{-4} for any two-year mission.

Table 4.5. Potential EVA Task Requirements for Extended Space Missions

Task Descriptions	Activities Required	Force Producing Requirements	Chance is Required
Repair Puncture			
-Space Radiator	Epoxy Patch	10-20 lbs in translation	$<1 \times 10^{-6}$
-Cabin Wall	Epoxy Patch		$<1 \times 10^{-4}$*
Replace			
-Engine Quad, RCS or Grav. Cont.	4 AN Bolts	40-70 in-lbs torque, 20 lbs in translation	
	2 AN Fittings	30-50 in-lbs torque	$<1 \times 10^{-5}$
	1 Elec. Conn.	5-8 in-lbs torque	
Replace Main Engine Gimbal Actuator	2 AN Bolts	50-100 in-lbs torque	
	2 Fasteners	10-20 in-lb torque, 20 lbs in translation	$<1 \times 10^{-5}$
	1 Elec. Conn.	5-8 in-lbs torque	
Replace Antenna, DSIF Drive Unit	8 AN Bolts	40-70 in-lbs torque	
	Elec. Conn.	5-8 in-lbs torque	$<1 \times 10^{-4}$**
	8 Fasteners	10-20 in-lbs torque, 20 lbs translation	
		TOTAL	$<2 \times 10^{-4}$

*Requiring EVA support
**Assumes use of backup antenna prior to EVA

5.0 CONCLUSIONS

The study demonstrated conclusively that, long duration, manned space flights can be made safely when designed around the availability concept. Further, it demonstrated that contemporary hardware can be used to fulfill many of the systems functional requirements.

Although the absolute value of the data presented herein may be open to question, their relative value and "ball park" levels are unquestionably valid. The data baseline used in this study is that taken from systems and components of known ability in terms of reliability and space rating. This factor alone is enough to assure confidence in the results. In addition, the designs employed these hardware elements in the same functions and environment wherein they were qualified.

Some of the more profound conclusions to be drawn relevant to the baseline mission are:

1. Much of the required hardware is available and nearly qualified.
2. Maintenance and repair is both feasible and desirable.
3. The operational concept can exert a pronounced influence on mission success and safety.
4. The unscheduled maintenance and repair work load required to support critical systems will be low, probably less than one in a three-day period.
5. The chance of an extra-vehicular maintenance action is expected to be less than 1/1000.
6. The chance of more than 260 M&R actions per two-year mission is expected to be less than 1/100.
7. The spares weight decrement will be low, about 900 pounds for unscheduled maintenance actions.
8. The module/assembly level is the optimum level for maintenance and replacement for most of the potential failures.
9. The required maintenance actions can be performed within the expected downtime constraints.

6.0 SIGNIFICANT CONTRIBUTIONS

The results of the study provided some significant contributions to space mission planning technology. These are elaborated on in Volumes I, II, and III; but, in summary, they involve:

1. Development of an extended mission design concept.

2. Definition of the space mission maintenance and repair problems.

3. Definition of system downtime physics.

4. Development of the technology associated with reducing and equalizing the failure hazard.

5. Development of an efficient mission simulation technique which permits assessment of mission success and design optimization around this factor.